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STANDARD BONDED REPAIRS FOR CORROSION DAMAGE

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NOTICE

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

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13. ABSTRACT *(Maximum 200 Words)* This report details experiments done to evaluate the effects of intense corrosive action on an area with a bonded repair over corrosion damage. Panels were pre-corroded and repaired using a variety of repair materials. The repaired specimens were then re-exposed to a corrosive environment to determine the effectiveness of the bonded repair in preventing additional corrosion. After re-exposure, evaluation of repaired specimens showed that the bonded repairs provided good protection from the corrosive environment provided the edges were effectively sealed. In addition, Boeing Wedge Test coupons and Single Lap Shear coupons were similarly exposed and re-exposed to a corrosive environment. All samples were well within acceptable tolerances for the adhesive. Effects of corrosion damage on fatigue life will be examined in future work.			
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Standard Bonded Repairs for Corrosion Damage

Advanced Repair Technology International

1. BACKGROUND

As aircraft fleets get older, corrosion damage becomes more and more of a significant maintenance issue. Historically, corrosion repair has been a secondary priority to aircraft designers. Much more attention has been given to fatigue related issues in ASIP style programs. Corrosion damage, however, is a significant factor in determining an aircraft's economic life.

Standard corrosion repair methods currently in use consist of removing visible corrosion damage and installing a riveted doubler to restore strength. A more efficient way of repairing corrosion damage would be to use bonded doublers to restore strength lost to corrosion. Bonded repairs use a structural adhesive to transfer load and do not require additional holes in the structure for rivets.

The repair evaluation portion of this study focused on whether or not corrosion grows underneath a bonded repair. The static evaluation portion of this study focused on the effect of corrosive exposure on adhesive properties. Moisture ingress into conventional corrosion repairs can lead to additional corrosion, especially around rivets.

This paper examines bonded repairs of corrosion damage to determine if corrosion growth on the substrate is limited or curtailed by subjecting test coupons to a corrosion-aggressive environment and evaluating the amount and form of corrosion growth.

1.1 Corrosion Growth Questions

What happens to active corrosion areas not visible to the naked eye left behind after the cleaning process is complete? These areas may be corrosion initiators that could cause corrosion growth inside the host structure leading to pillowing or exfoliation.

It is also unclear how much and what form of moisture composite patches and adhesives absorb during service. It is known that moisture absorbed into adhesives does not act simply as a group of water molecules, but actually a reaction occurs between the liquid and the adhesive thereby changing the adhesive chemistry. The effect this moisture-saturated adhesive could have on corrosion growth is unclear.

Some patches used in bonded repairs are made with composite materials or a metal different from the host structure. This could lead to galvanic action if saturated adhesive provided a clear electrical path between host and repair. Aluminum or steel rivets in graphite panels experience intense galvanic corrosion, but relatively little is known about the galvanic action in purely bonded joints where the adhesive itself acts as an insulating layer. Combination bonded-riveted joints, like those on some commercial transports, have been shown to incur significant corrosion damage, but these structures have multiple points of moisture entry and a different surface preparation process.

The most common examples of corrosion damage in bonded applications occur because of moisture ingress under disbonded joints. This disbonding is typically caused by inadequate surface preparation. This was not addressed by this study because the end goal of the work is to identify any corrosion growth occurring under properly installed permanent repairs. Also, any surface damage that would lead to a disbond is assumed to be found and repaired by routine maintenance.

This study attempts to answer the question: is corrosion growth curtailed by the proper application of a bonded repair, even in the presence of moisture and galvanic catalysts?

2. CORROSION TEST SETUP

The corrosion growth portion of the testing included the following steps:

- Chamber calibration
- Pre-exposure
- Specimen repair or coupon fabrication
- Re-exposure

Coupons were tested using a combination immersion/atmospheric exposure system that employed a modified version of the Copper-Accelerated Acetic Acid-Salt Spray (CASS) test as described in ASTM B 368-97. Coupon specifics are listed in Table 1.

Table 1: Repair Evaluation Configurations

Substrate	Repair Material	Samples
7075-T6	None	24
7075-T6	7075-T6	12
7075-T6	MB 1146	12
7075-T6	Graphite	12
7075-T6 with Holes	7075-T6	12
7075-T6 with Holes	MB 1146	12
7075-T6 with Holes	Graphite	12

Each patched coupon type was tested in two configurations. The primary configuration was simply a patch covering the specimen. The secondary configuration incorporated perforations in the substrate material. These holes accelerate moisture ingress at the bond and present a worst case scenario of leaking fasteners. The entire panel was repaired at one time, with the repair overlapping the panel slightly to ensure complete coverage of every specimen. The hole and specimen locations are shown in Figure 1.

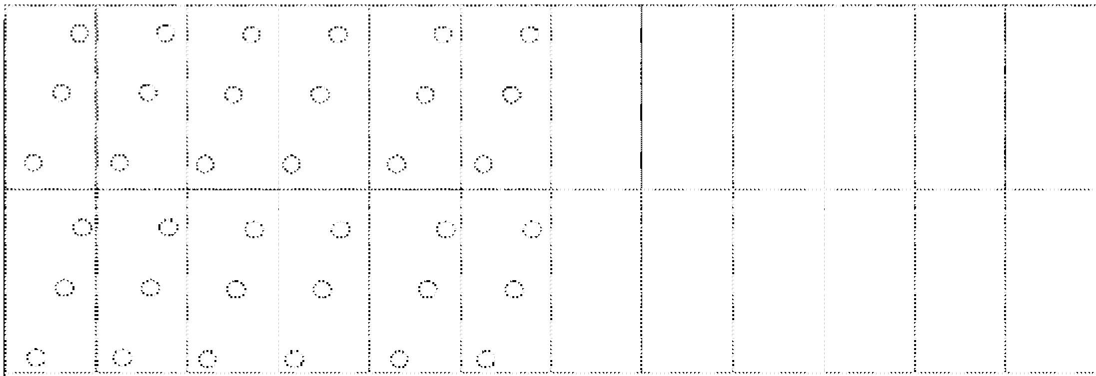


Figure 1: Diagram Of Hole And Saw Cut Locations

2.1 Corrosion Growth and Evaluation Procedure

In order to examine the effectiveness of bonded repairs for corrosion damage, corrosion must first be grown on the host material. This visual corrosion was removed by chemical and mechanical cleaning and the damaged areas repaired with standard bonded repair practices. Any microscopic corrosion was left behind, simulating conditions that might occur in the field. The specimens were then subjected to the corrosive environment again to cause corrosion to reinitiate under the bonded repair.

2.2 Corrosive Environment – ASTM B 368-97

The corrosive environment chosen for this test was a modified version of the Copper-Accelerated Acetic Acid-Salt Spray Testing (CASS Test) as described in ASTM B 368-97. The standard calls out a spray apparatus where the specimens are evenly misted with the CASS solution. The test as performed has been modified to be a half-immersion test with only one side of the specimen subjected to open corrosive attack. This was done to expose the samples to a more hostile environment thereby reducing the time spent in the corrosion chamber. Preliminary tests showed that corrosion pits are visible on both 2024-T3 and 7075-T6 specimens during the first week of exposure to the solution. Also, by immersing half of the specimen in solution, three environments were actually being tested: fully submerged, air/water interface (mist) and hostile air. This is important because no previous work had been found that identifies which corrosion inducing method is most effective for a sealed/repaired part. Noticeably different corrosion patterns were evident in each area. Each specimen was inclined between 15 and 30° from vertical to allow for condensation runoff. In preliminary testing, the highest amount of corrosion was shown to grow at the air/water interface on the face angled towards the solution. The test setup is shown in Figure 2 and Figure 3.

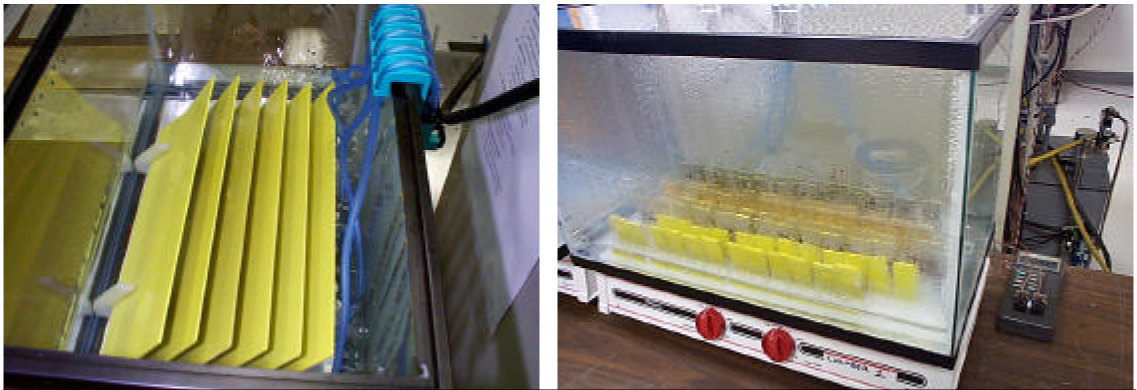


Figure 2: Corrosion Tank Setup For Repair Evaluation Panels And Specimens

2.3 Chemical Cleaning – ASTM G 1 – 90

Chemical cleaning of the specimens prior to weighing was necessary to accurately quantify the corrosion rate of the metal. Chemical cleaning is more precise than mechanical abrasion because the amount of mass loss due to the cleaning process is more controlled. The cleaning method used for this program was designation C.1.1 from ASTM G 1 – 90 for Aluminum and Aluminum Alloys.

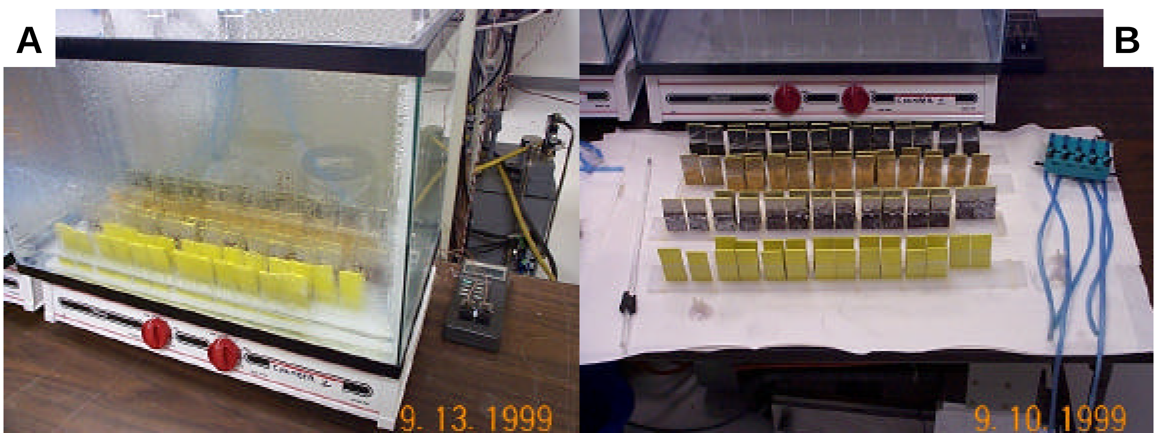


Figure 3: Repair Evaluation Specimens – A) in and B) out of tank

2.4 Repair Procedure

The specimens were repaired using standard ARTI procedures. This process was used on the corroded surface of the specimens. The general steps for bonded repair application are as follows:

- Remove all primer from specimens
- Abrade & wipe repair area with MEK and scotchbrite until no water breaks are present

- Abrade repair area with distilled water and scotchbrite then wipe with lint free tissue
- Grit blast repair area with 50 micron alumina oxide grit
- Apply & cure Silane coupling agent
- Apply & cure corrosion inhibiting primer BR-127
- Lay-up adhesive and repair then cure

2.5 Specimen Justification

Because of the nature of aircraft corrosion, the selection of the proper materials and configurations for the test program was important. This study's primary focus is corrosion on skin panels and other sheet-type structures. These structures are almost always riveted and experience a variety of field conditions.

2.6 Materials

7075-T6 was chosen as the host material because it has been shown to be very susceptible to corrosion in the field. Also, much of the heavy aircraft fleet has 7075 wing panels or control surfaces that are corrosion prone. 2024-T3 was considered but rejected because 7075 corroded faster and in a more controlled manner during preliminary testing.

Repair materials were chosen to represent different operating configurations. The most common strategy for corrosion repairs is 'replace like with like'. If 7075 is to be repaired, then 7075 should be the repair material. Therefore the default repair case was 7075-T6 on 7075-T6. The aluminum serves as an efficient barrier against moisture ingress because it does not absorb moisture and was expected to perform the best. A graphite prepreg repair was examined to understand what, if any, galvanic action initiated across a saturated bond. Also, an adhesive only repair acted as a worst case example, where the entire bond surface is completely exposed to moisture. This offered the best chance for the repaired area to be attacked by the corrosive solution and was deemed the most likely repair material to allow corrosion growth.

2.7 Configurations

Several configurations for the coupons were considered with the primary goal being to allow maximum access of corrosive fluid to the metal. Two configurations were decided upon:

- Solid panels and repairs
- Panels with holes and solid repairs

The second configuration simulates leaks around rivets and accelerates the moisture penetration into the adhesive. This allows maximum access to the adhesive and theoretically quickens the artificial aging process.

Only one side of the specimens was exposed during testing. The other side was primed with an epoxy polyamide primer. The entire specimen was cleaned and degreased, then all but the test face coated in primer. This ensured that the edges were covered since corrosion there is usually more severe than on rolled surfaces.

2.8 Equipment description

2.8.1 Corrosion Chamber

The corrosion chamber was a 10-gallon glass tank with a Plexiglas top. The specimens were supported at a 15 - 30° angle by a Plexiglas support fixture. The solution was aerated by an air pump with five outlets evenly spaced throughout the tank but not directly impinging on any specimens. The tank was heated by an external electric heater and a heat transfer plate. An external J-type thermocouple and an in-tank thermometer monitored tank temperature. Temperature points were mapped from tank locations and recorded when the solution was monitored.

2.8.2 Scale

The scale used to weigh the specimens and the ingredients of the solutions was an A&D HF300 balance. It is capable of a maximum measurement of 310 grams at a resolution of 0.001grams. The scale is calibrated using a two-point method at zero and 200 grams according to manufacturer specifications.

2.9 Visual Inspection

Visual inspection for corrosion damage was done using three different methods. Gross contamination was noted in the main visual record by taking digital photographs with a Kodak digital camera and archiving the pictures. Micrographic and Scanning Electron Microscope analysis with a 50x magnification was performed on selected specimens to show typical damage growth patterns.

3. REPAIR EVALUATION TEST PLAN

3.1 Chamber Calibration

The chamber was calibrated in accordance with the method specified in ASTM B 368-97.

3.2 Pre-Corrosion

Eight 4” x 13” x 0.63” 7075-T6 panels were cleaned with MEK and Scotchbrite to expose fresh surface. One side of the panels was primed with epoxy-polyamide primer, leaving one side fully exposed to the corrosive solution.

Specimens were placed in test tank noting date and time, test solution pH and batch number.

At the end of each test interval corrosion products were removed. The following data was recorded for each specimen.

- Unit and total immersion time
- Mass
- Visual corrosion grade

Each specimen was documented with a standard digital camera shot. Specimens were taken as necessary for micrograph analysis.

The test solution was refilled as required to maintain fluid level, recording batch number, temperature, amount and pH for the tank and additive, not exceeding once per day. The test solution was renewed every 7 days, rinsing the tank with distilled water between solution changes. The pH of the test solution was measured before disposal and included in lab records. The solution was neutralized as necessary for disposal.

This process continued for four weeks.

3.3 Repair Specimens

After final removal of all corrosion products, each panel was fully degreased and primed on one side, being careful to fully coat the holes. On the repaired panels, full ARTI surface preparation and curing guidelines were used to attach repairs. Holes were drilled in the substrates following the repair application. Twenty-four 1” wide specimens were cut from each panel and primer was applied to freshly exposed edges.

All test specimens and their location in the specimen holders were noted and each specimen’s length, width, thickness and mass were measured and recorded.

3.4 Re-Corrosion

Specimens were placed in the test tank noting date and time, the pH of the test solution and batch number.

At the end of each test interval the following test data was recorded for each specimen.

- Unit and total immersion time
- Mass
- Visual corrosion grade.

Each specimen was documented with a standard digital camera shot. The specimen location in the tank was rotated after each measurement and the location of each coupon was recorded.

The test solution was refilled as necessary as described above.

This process continued for four weeks or until an adequate corrosion level was reached.

4. CORROSION CALCULATIONS

Mass Loss

$$\Delta m = m_0 - m_i$$

% Mass Loss

$$\Delta m_{\%} = \frac{(m_0 - m_i)}{m_0} \times 100\%$$

Corrosion Rate

$$CR = \frac{\left(8.76 \times 10^4 \times \Delta m\right)}{\left(A \times t_T \times 2.81\right)}$$

This equation comes from ASTM G-16. Table 2 contains unit and variable definitions.

Table 2: Variable Key

Symbol	Definition	Units
M	Mass	Grams
T	Exposure time	Hours
CR	Corrosion Rate	Mm/year
A	Surface Area	Cm^2
I	Index	N/A
T	Total	N/A

4.1 Visual Grade

The visual grading scale rates the relative amounts of four different corrosion indicators. The scale for each point ranges from 0 (0 – 10 %) to 9 (90 – 100 %).

A – Pitting – indicates the amount of pitting corrosion evident during a visual inspection.

B – Hole Damage – indicates the amount of corrosion damage initiated at the access holes evident during a visual inspection.

C – Filiform – indicates the amount of filiform corrosion evident during a visual inspection.

D – Edge Damage – indicates the amount of corrosion damage initiated at the edge of the specimen evident during a visual inspection.

5. STATIC STRENGTH TESTING

5.1 Background

The effectiveness of a bonded repair is measured using the basic criteria of static strength and durability. The Repair evaluation part of this program used visual observation of corrosion growth to qualitatively assess the long-term durability of the repair. The assumption used was that significant corrosion growth translates into degraded durability. The static evaluation part directly measured the effect of environmental exposure on structural properties.

Two types of tests were performed. The Boeing Wedge Test (BWT) is the industry-accepted measure of bonding environmental durability. By performing this test, the effect of any corrosion growth can be directly assessed. The results show whether corrosion growth, if it occurs, affects this key factor of a bonded repair – the metal to adhesive interface.

Similarly, Single Lap Shear (SLS) tests determined the effect of corrosive growth on adhesive static shear strength. Bonding techniques with poor environmental durability show decreased static strength with time because the adhesive to metal interface degrades.

The basic procedure for the static evaluation paralleled those used for the repair evaluation. The following general steps were followed:

1. Pre-corrode panels
2. Fabricate specimens
3. Re-expose specimens
4. Test specimens

The test setup is shown in Figure 4.

Figure 4: Static Strength Panels - A) in and B) out of tank

5.2 Specimen Configuration

A total of seven configurations per test were chosen. They are:

- Ideal with and without holes (ideal)
- Baseline with and without holes (baseline)
- Pre-corroded with and without holes (normal exposure)
- Pre-corroded without holes and no mechanical cleanup (no cleanup)

Since the goal of this part of the work was to determine the effect of growing corrosion underneath a bonded repair on its mechanical properties, the normal exposure samples were the main data of interest. The baseline samples provide a fair comparison point to the normal exposure samples since bond-line saturation alone can affect the testing. Ideal specimens had no corrosion damage and no corrosive exposure and serve as a starting comparison point.

Some specimens had holes in them to allow maximum moisture penetration into the bond. For the wedge test specimens, the holes were evenly spaced over the top portion of the plate that the wedge was driven into. The lap shear specimens had holes in the test area between the metal cuts. Holes were drilled prior to cutting the individual specimens from the plates and removed less than 5% of the surface area.

The majority pit depth was measured by grinding one of the corroded panels until 90% of the corrosion damage was gone. All panels, including baseline, were then ground down to the thickness of the sample panel. This provided a realistic comparison by ensuring that the substrate stiffnesses were similar.

2024-T3 was chosen for the structural test so this data could be added to ARTI's existing test database. In addition, preliminary testing showed that the CASS solution grew corrosion acceptably on 2024-T3.

The no cleanup coupons were tested at the USAF's request. In this case, the wedge test and lap shear specimens were pre-corroded but the damage was not blended out. The corrosion products were removed using standard methods, but all pits remained. The test coupons were manufactured using standard ARTI surface preparation techniques, re-corroded and tested just like the other specimens.

Specimen information is listed in Table 3.

Table 3: Static Evaluation Configurations

Test Type	Material	Variable	Samples
BWT	2024-T3	Ideal	12
BWT	2024-T3	Ideal with holes	6

Test Type	Material	Variable	Samples
BWT	2024-T3	Baseline	6
BWT	2024-T3	Baseline with holes	6
BWT	2024-T3	Pre-corroded	6
BWT	2024-T3	Pre-corroded with holes	6
BWT	2024-T3	USAF condition	6
SLS	2024-T3	Ideal	6
SLS	2024-T3	Ideal with holes	6
SLS	2024-T3	Baseline	6
SLS	2024-T3	Baseline with holes	6
SLS	2024-T3	Pre-corroded	6
SLS	2024-T3	Pre-corroded with holes	6
SLS	2024-T3	USAF condition	6

5.3 Specimen Fabrication

The pre-corroded test coupons and the baseline coupons were cut from the appropriate plate pairs and the edges sealed with primer. Small holes (0.06” diameter) were drilled in the selected coupons to allow for maximum moisture ingress. The coupons were subjected to the corrosive solution again to attempt to reinitialize corrosion growth.

The coupon configurations are shown in Figure 5.

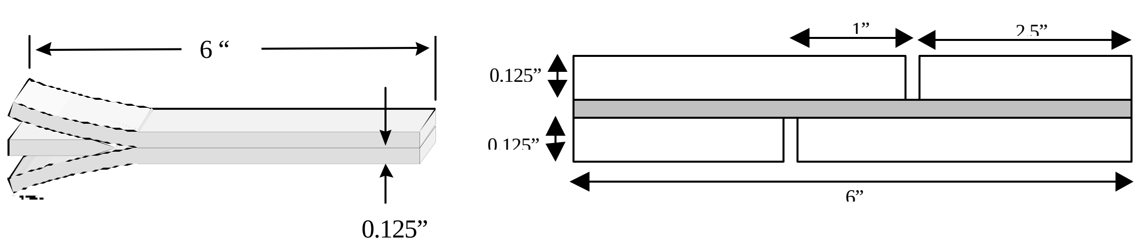


Figure 5: Boeing Wedge Test and Single Lap Shear Specimens

The corrosion process used for this portion of the program was the same solution and general tank configuration described above. The only difference being that the coupons were flat on racks completely submerged in the solution in order to achieve a uniform amount of corrosion damage. Since only a small portion of the coupon area is being directly tested, it was important to ensure uniform corrosion damage. This minimized the effects of severe localized corrosion damage.

After the specimens were submerged in the corrosive solution for the appropriate time, they were removed and rinsed in distilled water to ensure the removal of the solution. The specimens were allowed to air dry at room temperature for 24 hours and dried in an oven at 120° F for 16 hours to minimize the effect of wet adhesive. After drying, the specimens were tested per the governing standard at an independent lab.

5.4 Data

The BWT and SLS tests were chosen for this exercise because they are simple measures of bonded repair effectiveness.

The BWT is the primary evaluator of bonded repair durability. The test qualitatively compares the performance of a bonding process to a value that has been shown to represent environmental durability in the field. The specimens were tested by ARTI per ASTM D-3762. Key test parameters are listed below.

- Adherend – 2024 –T3 Aluminum
- Test environment – 7
- Report surface condition and average crack growth for each specimen after 24 hrs and 72 hrs

SLS tests were conducted to measure the static shear strength of the adhesive. The tests were conducted in a tensile test machine at room temperature. The coupons were placed in the machine and loaded until the adhesive layer failed, per ASTM D-3983. Key test parameters are listed below.

- Adherend – 2024 – T3 Aluminum
- Test speed – 750 psi of bond area / min = 375 lbs. / min
- Report surface condition and maximum load carried by specimen at failure

6. RESULTS

6.1 Repair evaluation data

The bare panels were exposed in the CASS solution for two weeks, inverted and exposed for another two weeks. The corrosion level at that point was significant with average pit depths on the order of 0.1 inch. The corroded panels were repaired, cut into specimens and re-exposed in the CASS solution, oriented such that the waterline on the specimens was the same as the original waterline on the panels.

After two weeks of exposure, significant corrosion damage was observed on the non-repaired specimens. Large amounts of salt had also condensed on most of the other specimens as well. It was decided to halt the test at this point and examine two of each specimen type for damage levels. The non-repaired specimen showed severe pitting as well as exfoliation around the edges. The adhesive-only specimen was discolored in some areas leading to the belief that corrosion growth was occurring under the adhesive. Although some slight filiform growth was noted, the adhesive specimens seemed in relatively good shape. Neither the graphite nor the metal specimens examined showed significant corrosion activity under the repairs, however the edges of the graphite specimens were damaged.

Due to this information, half of the non-repaired and the adhesive only specimens were removed for final evaluation (odd numbered specimens 1-11 and even numbers 14 - 24) and the rest of the specimens were returned to the corrosion chamber for an additional two weeks of exposure.

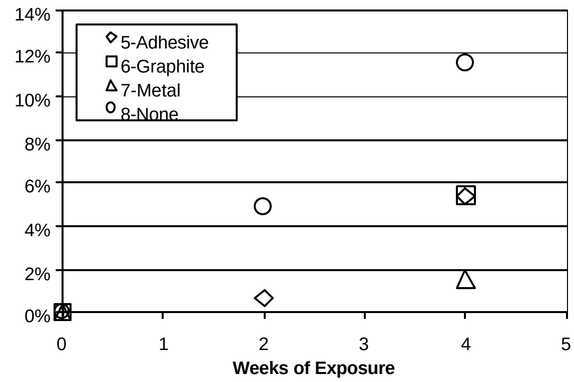
The repair evaluation mass loss data is very close to what was expected. Through four weeks of exposure, the specimens lost an average of:

- Non-repaired – 11.5%
- Adhesive-only – 5.4%
- Graphite – 5.4%
- Metal – 0.7%

Significant two-week data was collected for only the non-repaired and adhesive only specimens, which lost:

- Non-repaired – 4.9%
- Adhesive-only – 0.7%

The average percent mass loss and corrosion rate data is shown in Figure 6 and Table 4.



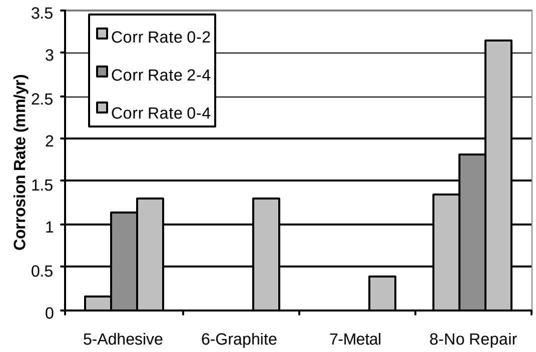


Figure 6: Repair Evaluation % Mass Loss and Corrosion Rate Graphs

Table 4: Repair Evaluation Data

Specimen Type	Average Initial Mass (g)	Average Mass @ 2 Weeks (g)	Average Mass @ 4 Weeks (g)	Total % Mass Loss	Total Corrosion Rate (mm/yr)
No Repair	7.618	7.245	6.741	12%	3.2
Adhesive	6.694	6.649	6.334	5.4%	1.3
Graphite	6.728	N/A	6.364	5.4%	1.3
Metal	6.771	N/A	6.667	1.5%	0.38

Qualitatively, the specimens showed several different types of corrosion and access patterns. The non-repaired specimens were severely pitted, but most of the pitting occurred at or slightly above the water line in the air/water interface zone. This was expected because a wet/dry/wet environment is very severe for corrosion growth. Although there was pitting both under the waterline and above it, the primary form of corrosion in these zones was actually filiform.

The adhesive-only specimens showed pitting and filiform damage. The damage was not nearly as severe as the non-repaired specimens, but was more severe than any of the repaired specimens. Again, this was as predicted. Notably however, the damage was diffused rather than primarily located at the water line.

The graphite repair specimens showed small amounts of pitting and filiform corrosion, but an inordinate amount of edge damage. Some specimens exhibited complete exfoliation from the edges that reduced the total area by up to 10%. In areas not affected by either edge or hole initiated corrosion there was very little, if any corrosion damage. Figure 7 shows the average qualitative damage levels of each specimen type.

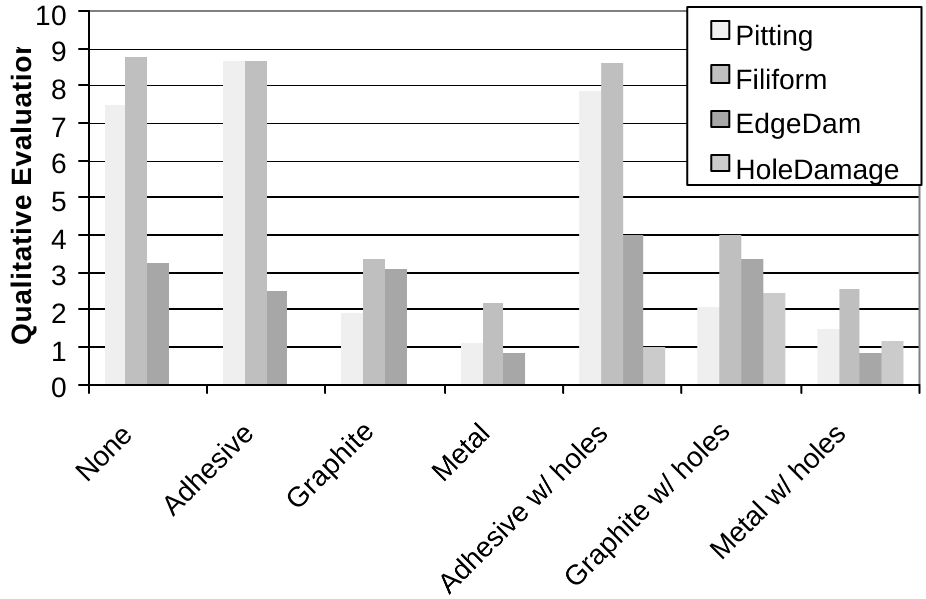


Figure 7: Qualitative evaluation of repaired specimens

The metal repair specimens showed very little corrosion damage. There was a small amount of filiform, and a few very small pits on some samples, but the majority of specimens showed practically no damage. The damage that was present initiated on the edges and at the holes.

Damage maps of all the specimens are shown in Figure 8 and Figure 9. Qualitative average damage assessments are shown for all specimens in Table 5 and Table 6.

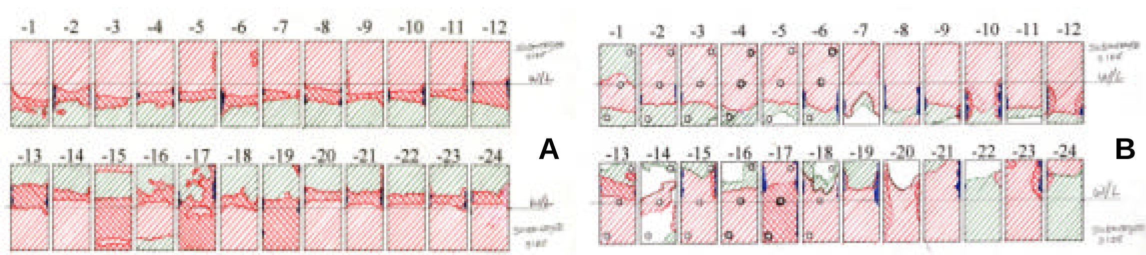


Figure 8: Damage Maps - A) no repair B) adhesive

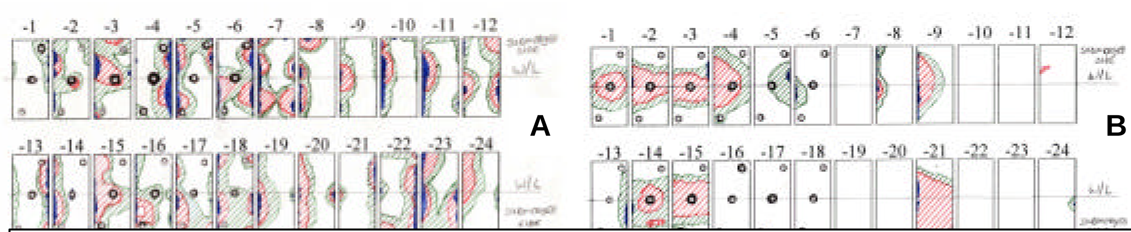


Figure 9: Damage Maps - A) graphite B) metal

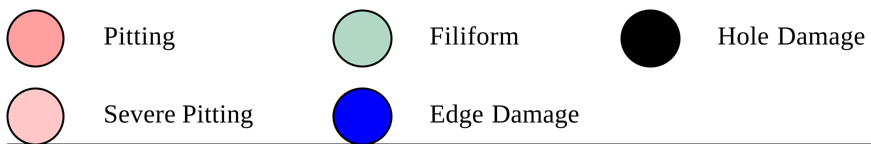


Figure 10: Damage Map Key

Table 5: Repair Evaluation Without Holes Qualitative Data

Specimen Type	Average Pitting Damage	Average Filiform Damage	Average Edge Damage
No Repair 2 Weeks	7.0	8.7	1.3
Adhesive 2 Weeks	6.5	7.9	1.0
No Repair 4 Weeks	7.5	8.8	3.3
Adhesive 4 Weeks	8.7	8.7	2.5
Graphite 4 Weeks	1.9	3.3	3.1
Metal 4 Weeks	1.1	2.2	0.8

Table 6: Repair Evaluation With Holes Qualitative Data

Specimen Type	Average Pitting Damage	Average Filiform Damage	Average Edge Damage	Average Hole Damage
Adhesive 2 Weeks	4.2	7.3	1.0	0.0
Adhesive 4 Weeks	7.8	8.6	4.0	1.0
Graphite 4 Weeks	2.1	4.0	3.4	2.4
Metal 4 Weeks	1.4	2.5	0.8	1.2

6.2 Static evaluation data

The BWT is a qualitative indicator of structural bond durability. At ARTI, a pass/fail value of less than 0.2 inches is used to qualify adhesives, new processes and bonding materials. If the measured crack growth after 24 hours does not exceed this value, the adhesive, process or material is considered acceptable for structural bonding based on twenty five plus years of field experience both in the United States and Australia.

No specimens of any configuration failed the Boeing Wedge Test. The average crack growth increased from ideal to baseline. From baseline to normal exposure, the crack growth stayed relatively constant. There was an increase in crack growth between normal exposure and no cleanup coupons, but all specimens did pass the test. The data is presented in Figure 11.

The SLS test is used to determine the shear strength of the adhesive. Any adhesive has a characteristic shear strength value that can vary depending on the conditioning of the specimens. The SLS coupons were tested in the same configuration as the BWT coupons with similar results.

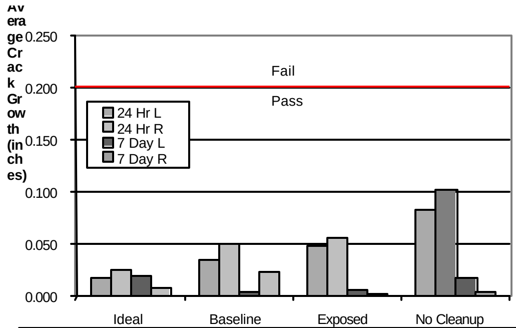
The maximum variation of average load at failure for all configurations was 13% between the no cleanup without holes and baseline without holes. The baseline values were highest. The other configurations were lower by:

- Ideal – 4.0%
- Normal exposure – 8.6%
- No cleanup – 13%

These percentages are all for coupons without holes. The coupons with holes had lower values than the coupons without holes. They did however follow the same general trend as the values of the coupons without holes, with the exception that the baseline average was essentially the same as the ideal average. The with holes configurations were less than the without hole configurations by:

- Ideal – 4.2%
- Baseline – 9.1%
- Normal exposure – 4.4%

There were no holes in any of the no cleanup specimens. The data is presented in Figure 11, Table 7 and Table 8.



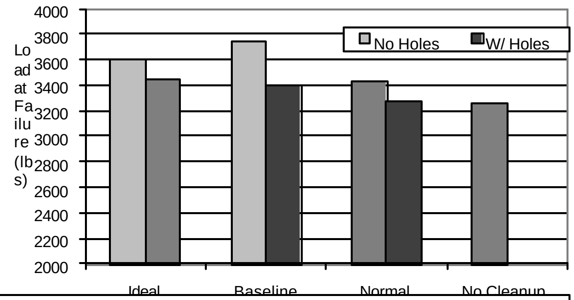


Figure 11: Boeing Wedge Test and Single Lap Shear Data

Table 7: Boeing Wedge Test Average Data

Coupon	24 Hr Growth (in)	7 Day Growth (in)
Ideal	0.021	0.013
Baseline	0.043	0.014
Normal Exposure	0.051	0.003
No Cleanup	0.092	0.010

Table 8: Single Lap Shear Average Data

Coupon	Load at Failure without Holes (lbs)	Load at Failure with Holes (lbs)
Ideal	3604	3451
Baseline	3750	3407
Normal Exposure	3428	3277
No Cleanup	3266	N/A

7. SUMMARY

Taken as a whole the data paints a clear picture of the effectiveness of bonded repairs for corrosion damage. That picture is consistent with long term experience with bonded repairs for any type of damage. Principally, the quality of a bonded repair depends on how it is installed and protected. A bonded repair can be very effective if it is installed and protected properly, but it can be susceptible to environmental effects if not properly installed and protected.

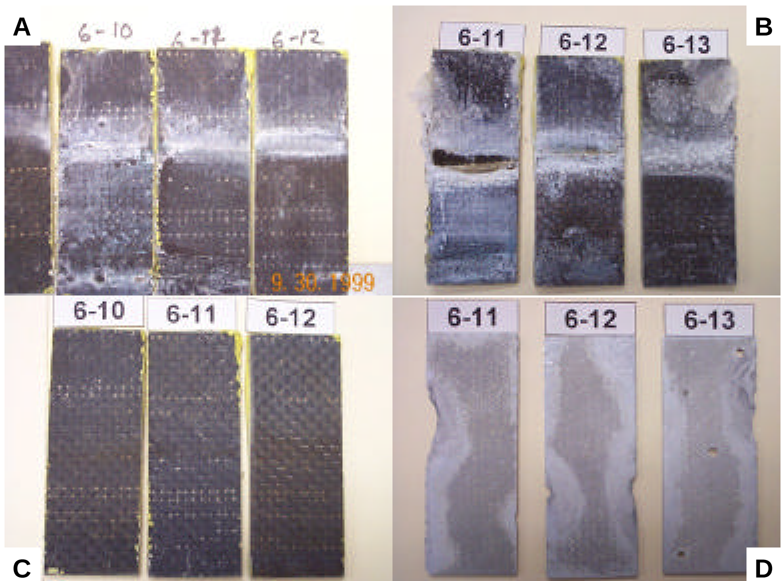


Figure 12: Graphite Repair Specimens - A) 2 wks B) 4 wks no cleanup C) 4 wks rinsed D) 4 wks cleaned

For example, the graphite specimens from the repair evaluation phase were damaged not by moisture penetrating the repair material and adhesive layer, but through the repair edges. The excessive edge damage can be traced to the way the specimens were fabricated. The repaired panel was cut using a band saw moving from the graphite through the aluminum. Although the specimen edges were protected by a thin layer of epoxy-polyamide primer, graphite fiber and dust was most likely embedded in the edges of the aluminum during the cutting process and then painted over with primer. This formed a galvanic couple, which ate away at the metal edges causing cracks in the primer layer and allowing direct exposure to the CASS solution. The addition of the corrosive fluid to the existing galvanic couple created a dynamic corrosion environment that destroyed the edges of some of the graphite specimens. It is important to note however that even on specimens with very bad edge or hole damage, there were portions of the specimens that were almost completely undamaged. The moisture that propagated through the adhesive was not enough to initiate corrosion, or cause previously repaired microscopic corrosion pits to re-initiate. These results clearly show how important it is that poor machining technique or inadequate cleanup is not allowed to create a galvanic couple.

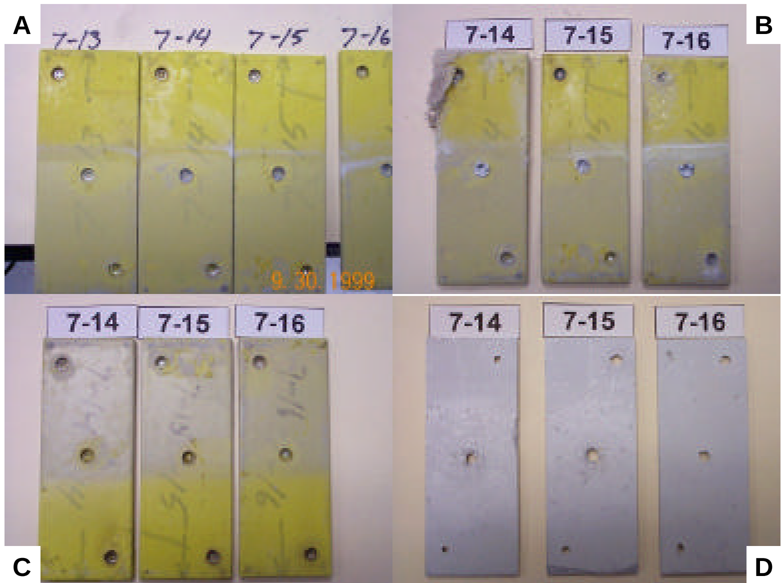


Figure 13: Metal Repair Specimens - A) 2 wks B) 4 wks no cleanup C) 4 wks rinsed D) 4 wks cleaned

The metal to metal bonded repair reinforced the belief that bonded repairs are good choices for corrosion sensitive areas. The metal and adhesive provided a very successful barrier against moisture ingress and without an electrolyte, corrosion becomes next to impossible. The only signs of damage on the metal specimens were where moisture was allowed direct access to the specimens through holes, simulating unsealed rivet holes, or poor sealing around the edges. Even when access was permitted; no major corrosion damage was present. The results of the non-repaired specimens show that this was a fairly extreme environment, which only further highlights the lack of significant corrosion damage on the metal and graphite coupons. Even the adhesive-only specimens showed a dramatic increase in protection over the non-repaired specimens.

It is also important to note the type of corrosion growth that occurred. Around the edges and holes, exfoliation was the primary mode of corrosion. That was expected since 7075-T6 is notoriously susceptible to exfoliation when edges or grain boundaries are exposed. More interestingly however was the apparent corrosion 'order of battle'. Filiform type corrosion seemed to occur before pitting in almost every specimen. Wherever pits were evident, there was always peripheral filiform damage. In cases where pits were not visible, filiform damage was present. This was initially observed during the solution run-off testing where the specimens were examined daily. Filiform damage would start at the air/solution interface and spread from there. Pitting would then initiate from the area where filiform damage was most prevalent, and move following the same pattern as the filiform damage.

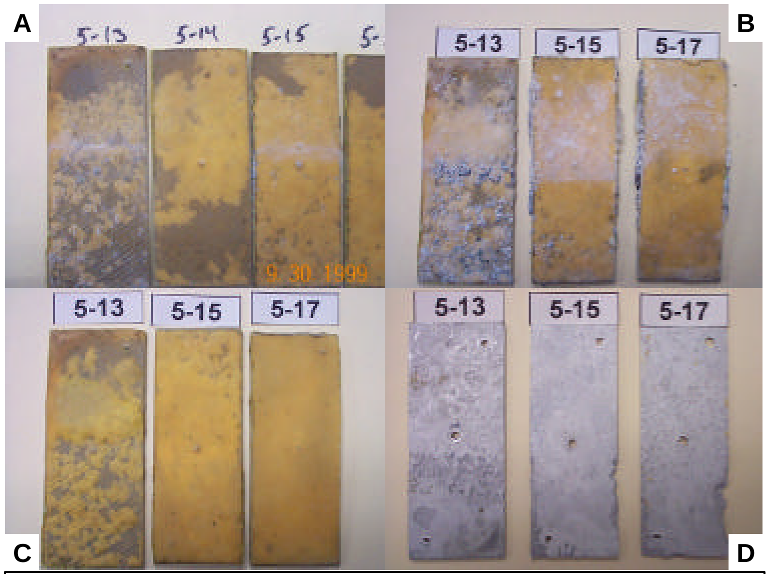


Figure 14: Adhesive Repair Specimens - A) 2 wks B) 4 wks no cleanup C) 4 wks rinsed D) 4 wks cleaned

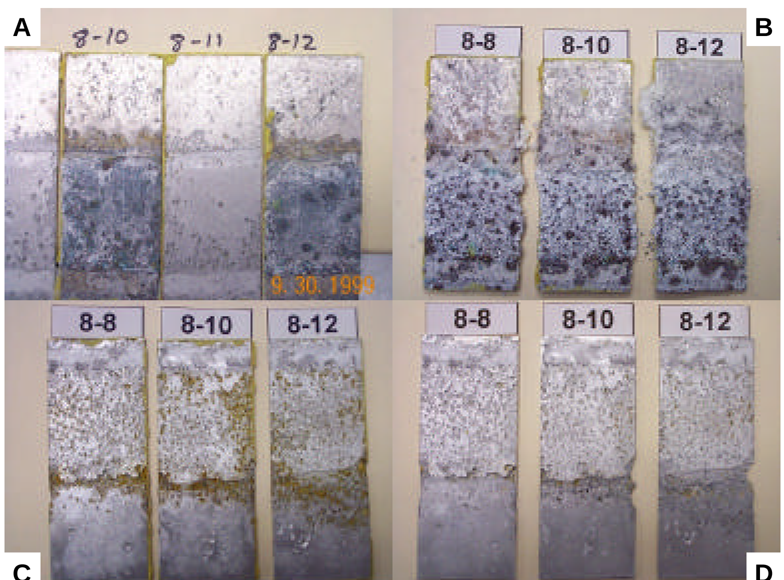


Figure 15: No Repair Specimens - A) 2 wks B) 4 wks no cleanup C) 4 wks rinsed D) 4 wks cleaned

In addition, as shown in Figure 16 through Figure 18 (micrographs of corrosion damage that was then chemically and mechanically cleaned) microscopic corrosion pits remained even after thorough cleaning. The panels were all cleaned as if they were aircraft parts. The damage was completely removed using standard sheet metal techniques and there was no visible corrosion remaining. This damage however did not regrow after re-exposure to the corrosive fluid. This was due to the repair and adhesive providing an effective barrier against moisture ingress. A riveted repair, with more moisture access points could not do as good of a job keeping moisture away from the remaining corrosion damage sites.

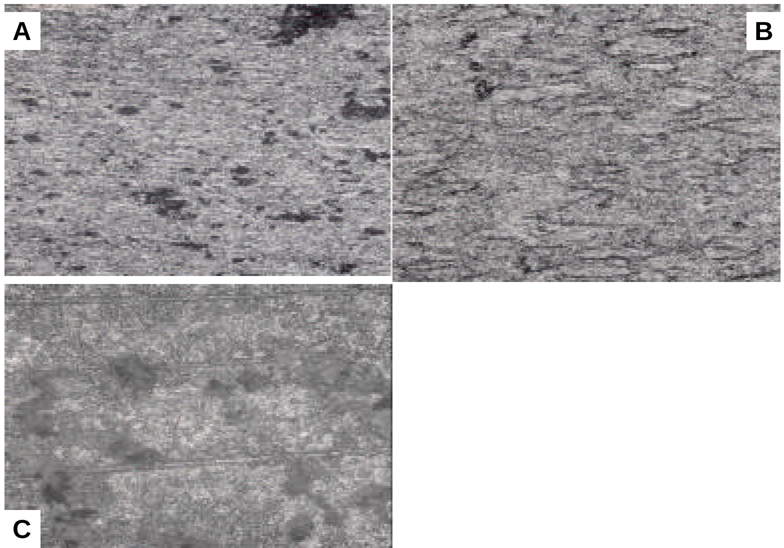


Figure 16: No Repair Specimen 8-12 – A) pre-corrosion B) solvent scrub C) 4 wks exposure

Just as the edge and hole damage in the repair evaluation specimens show that proper sealing is imperative in bonded repair installation, the lack of major variation in structural properties of the adhesive during the static evaluation testing demonstrated that with proper surface preparation bonded repairs can be very effective against any environment.

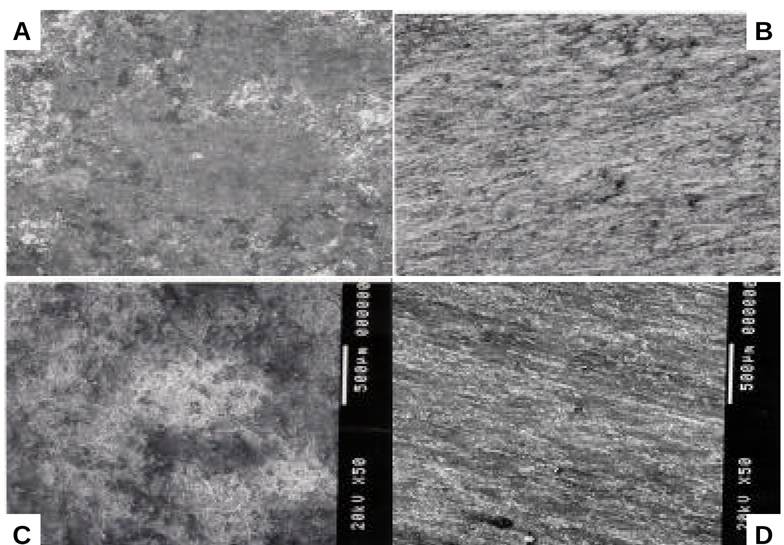


Figure 17: Adhesive Repair Specimen 5-13 –A) & C) after pre-corrosion B) & D) after solvent scrub

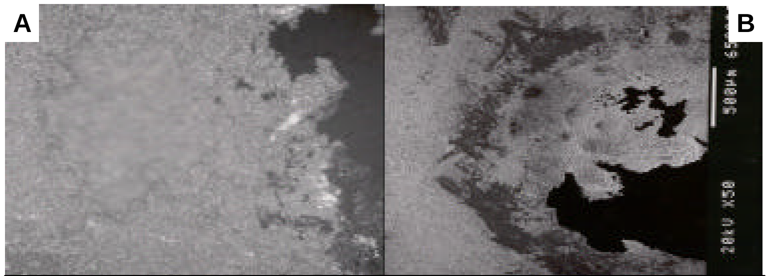


Figure 18: Adhesive Repair Specimen 5-13 – 4 wk exposure

The BWT data, the primary test of bond durability, showed conclusively that even if all pits are not physically removed that the bond could withstand extreme environmental conditions and still perform adequately. Similarly, the SLS data highlighted the fact that even under high environmental pressures, the adhesive does not break down and will continue to transfer design loads. When holes were drilled to allow more access to the bond-line, the data shows that both crack growth in the BWT and load at failure in the SLS coupons were worse than the corresponding data without holes. This however was basically just an offset. In the SLS data, where less coupon-to-coupon variation is expected, the offset was approximately 4%. This was primarily due to the loss of bond area caused by drilling holes in the test area. The holes were designed to allow maximum access to the bond-line by drilling completely through only one side of the coupon and exposing the entire surface of the adhesive in the hole to the corrosive solution. Since even with this extra access there was little to no property degradation, the data shows that the bonded joint would perform as designed even under extreme environmental exposure. The effects of corrosion on fatigue performance will be evaluated in a later program.

8. CONCLUSION

This research has shown that given proper surface preparation and adequate edge protection, bonded repairs are very effective for corrosion damage. They both protect the substrate from moisture ingress and re-initiation of remaining corrosion damage, and continue to provide design strength and durability even under extreme environmental exposure.

9. ACKNOWLEDGMENTS

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Special thanks are in order for ARTI technicians Mike Shupick and Mikel Shilling who manufactured and monitored the specimens.

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